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SENSIBLE AND LATENT HEAT LOSSES FROM OCCUPANTS OF SURVIVAL SHELTERS

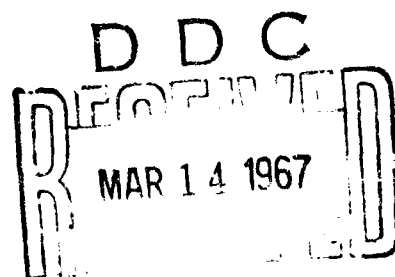
OCCUPATIONAL HEALTH RESEARCH AND TRAINING FACILITY

December 1966

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SENSIBLE AND LATENT HEAT LOSSES FROM OCCUPANTS OF SURVIVAL SHELTERS

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CINCINNATI, OHIO

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Through the

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PUBLIC HEALTH SERVICE
DIVISION OF HEALTH MOBILIZATION

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SENSIBLE AND LATENT HEAT LOSSES
FROM OCCUPANTS OF SURVIVAL SHELTERS

SUMMARY

Six figures have been prepared showing the sensible and latent heat exchange rates from clothed and nude individuals at various environmental conditions and at three metabolic rates. Data are also included by which the heat exchange rates for the "standard individual" may be corrected for "non-standard" groups.

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INTRODUCTION

Man's survival requires that, except for short periods of time, a rather accurate balance must be maintained between the rate of metabolic heat production within the body, and the rate of heat loss from the body to the surrounding environment. At normal environmental conditions, both sensible heat and latent heat (moisture) are given up by the body, and these in turn, tend to raise the temperature and humidity of the ambient air. In homes or other spaces having low population density, the changes in environmental conditions due to the heat given off by the occupants are quite small. However, in places of public assembly having high population density, the sensible heat and moisture contribution from the occupants can have a marked effect on the ambient conditions, and adequate ventilation or cooling is required to maintain a comfortable environment.

In times of emergency, a survival shelter will become a place of public assembly and may be expected to have a high population density. Except in rare instances, complete air conditioning will not be available and the entire metabolic heat production of the shelter occupants will have to be removed by ventilation, or by heat transfer to the exterior surfaces of the shelter.

The ventilating system for the average shelter will be designed, not to provide complete comfort for the occupants, but to enhance their chances of survival during the required period of occupancy. The amount of ventilation air that can be supplied may be minimal for several reasons. In case of disaster, public power supply cannot be relied upon, and ventilating fans may have to be operated manually by the shelter occupants, or by power from a small engine-generator unit within the shelter, if one is available. The outside air is also likely to be contaminated in case of disaster, and equipment will probably be provided for treating only a minimal amount of air.

The designer of the ventilating system for a survival shelter needs accurate data on the sensible heat and moisture loss from the human body, to establish realistic design requirements. This need has long been recognized by the Office of Civilian Defense, and a request for such data was made to the Occupational Health Research and Training Facility of the U. S. Public Health Service in Cincinnati. The request specified that the data should cover the following ranges of conditions:

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- (a) Dry-bulb temperatures - 50 to 120 F
- (b) Air velocities - still air and 100 ft./min.
- (c) Mean radiant temperatures - from 10 F below to 10 F above air temperature
- (d) Metabolic rates - 300, 400 and 600 Btu/hr.
- (e) Clothing - standard and minimal

It was further requested that the results should be presented in such a way that they could be made applicable to children and adults, male and female.

BACKGROUND

The temperature of the human body remains relatively constant over a wide range of environmental conditions. This is the result of the close balance which is maintained between heat production within the body (metabolism) and the heat loss from the body. The heat interchanges involved in this heat balance are described by the equation:

$$M = E \pm R \pm C \pm S \quad (1)$$

Where:

- M = rate of metabolic heat production within the body
- E = rate of evaporative heat loss
- R = rate of radiative heat loss or gain
- C = rate of convective heat loss or gain
- S = rate of heat storage within the body, resulting in a change in body temperature

The rate of metabolic heat production, M, is always positive. Under ordinary conditions, when the skin temperature is higher than the dew point of the air, E is also positive. R and C are positive when the skin temperature is higher than that of the surrounding walls and air, but negative when it is lower. Storage, S, is positive when the body is gaining heat and its temperature is rising, and negative when the rate of heat loss exceeds M, and the body temperature is falling. While the body can store or lose heat for short periods of time without serious consequences, in spaces intended for prolonged occupancy conditions must be such that S = 0.

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Ideal conditions are experienced when the metabolic heat, M , is just balanced by the minimal evaporative loss plus radiation and convection. As environmental temperatures increase, R and C losses decrease and E increases to maintain the necessary heat balance. When the skin, air and surrounding surface temperatures are equal, R and C become zero and E must equal M . If ambient air and surface temperatures are above skin temperature, the body gains heat by radiation and convection (R and C become negative), and E must equal the arithmetic sum of $M + R + C$. For a more complete discussion of the adaptations of the human body to varying environmental conditions see References 1 and 2.

Some of the more important factors which influence heat exchange between the human body and its environment are air temperature, humidity, air motion, temperature of surroundings, activity, and the type and amount of clothing. There are also human factors such as age, sex, acclimatization and individual variability to further complicate the problem (see Reference 3).

In view of the many variables involved, it is not surprising that different investigators have arrived at somewhat different conclusions regarding heat losses from the body.

CALCULATION OF HEAT LOSS DATA

The equation for sensible heat loss from the body ($R + C$) which was judged to be best suited to this particular problem, is given by Burton⁽⁴⁾. It is applicable to both nude and clothed subjects. Assuming the average man to have a body surface of 20 square feet, the equation may be written:

$$R + C = 22.8 \frac{t_s - t_a}{I_c + I_a} \quad (2)$$

Where:

- $R + C$ = sensible heat loss from the average man, Btu hr
- t_s = skin temperature, deg. F
- t_a = air temperature, deg. F
- I_c = insulation of clothing, in clo units
- I_a = insulation of air, in clo units

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The clo⁽¹⁾, defined in terms of resistance rather than conductance units, is

$$0.88 \frac{\text{Deg. F}}{\text{Btu}/(\text{hr})(\text{sq. ft.})}$$

or

$$0.18 \frac{\text{Deg. C}}{\text{kg. -cal.}/(\text{hr})(\text{sq. m})}$$

The ordinary business suit has an insulating value of approximately 1 clo.

SKIN TEMPERATURES

Available data on mean skin temperatures at various air temperatures and velocities show considerable variation at the lower air temperatures. However, at air temperatures above 90 F, the data are in good agreement. Skin temperatures used in this study are plotted in Figure 1. Curves of skin temperatures for clothed subjects were constructed on the basis of data from several sources.^(5,6,7) Skin temperatures for nude subjects were plotted from an equation given by Gagge, et al.⁽⁶⁾ The questionable accuracy of skin temperature data at lower air temperatures is not considered important in this study. In practice, if a shelter environment is cool or cold, the shelter occupants would put on additional clothing to provide comfort. Enough clothing should be worn so that the total heat loss from the body will not exceed the metabolic rate.

CLOTHING

Data were requested for shelter occupants wearing standard and minimal clothing. For standard clothing, an ordinary business suit has been assumed. The value of I_c for such clothing, when dry, is approximately 1 clo, and this value has been used in the calculation of heat losses from clothed subjects.

Shorts for men and halter and shorts for women would probably constitute minimal attire. The heat losses from occupants in minimal clothing would be essentially the same as from nude subjects, particularly after the clothing becomes wet with perspiration. Data have therefore been calculated for nude subjects, for whom $I_c = 0$.

The insulation of the air, I_a , is a function of the air velocity. Values of I_a are plotted in Figure 2.⁽⁹⁾ The air velocity for which I_a values should be selected varies with the activity of the subject. At elevated metabolic rates the activity of the subject results in additional air

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movement over the body which must be added to the normal air motion of the environment to obtain the effective velocity. A table of these air-velocity corrections for various metabolic rates is given in Reference 3. In this study normal air velocities of 30 and 100 feet/min. have been increased to 80 and 150 feet/min., respectively, for calculation of heat losses at a metabolic rate of 600 Btu/hr.

RESULTS

Equation 2 has been used to calculate sensible heat losses, $R + C$, from the human body for various air temperatures and air velocities. The latent losses, E , were then calculated to satisfy the heat balance equation (No. 1) assuming no positive heat storage. The results are plotted in Figures 3 through 8. Figures 3, 4, and 5 are for clothed subjects and 6, 7, and 8 for nude subjects. The scales along the left side of each figure show the heat loss rates from an average man having a surface area of 20 square feet. The right hand scale gives heat loss rates per square foot of body area.

In Figures 3 through 8 the mean radiant temperature (MRT) is assumed to be the same as the air temperature. However, the figures may also be used for conditions where the MRT differs somewhat from the air temperature by considering the effective environmental temperature to be the mean of the air temperature and the MRT.^(4,5) For example, if body heat loss is desired for an environment where the air temperature is 90 F and the MRT 100 F, the answer can be found along the 95 F line.

Values from Figures 3 through 8 are for the average person having a surface area of 20 square feet and a supine resting metabolic rate of 300 Btu/hour or 15 Btu/hour per square foot of body area. Body area varies widely from person to person, and the metabolic rate per square foot of surface area varies somewhat with age and sex. To provide data for modifying the heat transfer rates given in the figures, so that they may be made applicable to non-standard groups of individuals, Table 1 and Figures 9 and 10 have been included. Table 1 gives the average height and weight of white males and females of various ages in the United States. Data for the table were taken from Reference 10. The approximate body surface area may be determined from the DuBois Body Surface Chart of Figure 9. The average supine resting metabolic rate per square foot of body area for males and females from six to sixty years of age may be obtained from Figure 10. The curves in this figure were plotted from Boothby, et al.⁽¹¹⁾

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The ratio of the average metabolic rates of "standard" and "non-standard" groups of individuals, when at rest or doing comparable light work, is approximately the same as the ratio of their supine resting metabolic rates. The metabolic rate, M_x , of the average individual in a "non-standard" group may therefore be approximated by the equation:

$$M_x = \frac{M_{dx} \times A_x \times M}{300} \quad (3)$$

Where:

- M_{dx} = supine resting metabolic rate of "non-standard" individual as determined from Figure 10 - Btu/(hr) (sq. ft.)
- A_x = body surface area of the "non-standard" individual from Figure 9 - square feet
- M = metabolic rate of the "standard" man at the indicated activity - Btu/hour
- 300 = supine resting metabolic rate of "standard" man - Btu/hour

The sensible heat loss from the average individual in a "non-standard" group, under the environmental and activity conditions postulated in Figures 3 through 8, may be calculated by the equation:

$$h_{sx} = A_x \times h_s \quad (4)$$

Where:

- h_{sx} = sensible heat loss from the "non-standard" individual, Btu/hour
- A_x = body surface area of the "non-standard" individual, square feet
- h_s = sensible heat loss as given in the right hand scale of the appropriate Figure 3 through 8 for the standard man, Btu/(hr)(sq. ft.)

The latent heat loss from the non-standard individual is the algebraic sum of his metabolic rate and sensible heat loss:

$$E_x = M_x - h_{sx} \quad (5)$$

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EXAMPLE

Determine the sensible and latent heat loss from an average 14 year old nude boy seated at rest in a room in which the air temperature is 100 deg. F, the MRT is 110 deg. F, and the air velocity is 100 feet/min.

SOLUTION

From Table I, the average 14 year old boy is 63 inches tall and weighs 108 pounds. From Figure 9, his average surface area is 16 square feet.

Figure 10 indicates a supine resting metabolic rate of 17.1 Btu/(hr)(sq. ft.) for a 14 year old boy. Using Equation 3, his metabolic rate when seated at rest:

$$M_x = \frac{17.1 \times 16 \times 400}{300} = 365 \text{ Btu/hour}$$

The sensible heat loss can be determined by Equation 4. In this case the mean of the air temperature and the MRT is 105; and from Figure 7, h_s is found to be -22 Btu/(hr)(sq. ft.).

Total sensible heat loss:

$$h_{sx} = 16 \times -22 = -352 \text{ Btu/hour}$$

From Equation 5, latent heat loss:

$$E_x = 365 - (-352) = 717 \text{ Btu/hour}$$

MODIFYING EFFECTS OF WET CLOTHING

As indicated above, the data shown in Figures 3, 4 and 5 for clothed individuals were calculated on the basis of dry clothing ($I_c = 1$). It is quite evident that at the upper end of the temperature range shown in the figures, an occupant of a shelter will perspire freely and any clothing worn will become damp or wet. Some discussion of the effect of wet clothing is therefore in order.

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It is generally agreed that as clothing becomes wet its insulating value decreases. There is no accepted basis for predicting either the degree of wetness which clothing will attain under a given set of conditions, or the resulting change in its insulating value. Lee and Henschel⁽³⁾ used an insulating value for wet clothes (I_{cw}) of 0.4 clo. If this value instead of the value for dry clothing were used in Equation 2, the sensible heat gains at the higher temperatures would be increased 48 and 64 percent, respectively, for air velocities of 30 and 100 feet per minute. This increased heat gain would be balanced by a corresponding increase in latent heat loss. The latent loss shown in Figure 4 at 120 F and 100 feet per minute velocity would increase from 750 to 975 Btu/hr.

It is also generally agreed that as clothing becomes wet the cooling efficiency of sweat evaporation decreases. When evaporation takes place from wet clothing instead of from the skin surface, a part of the heat required for that evaporation is supplied by the air instead of the body. The cooling efficiency may be defined as the ratio of the heat removal from the body by evaporation, to the heat which would be required to evaporate all of the sweat produced by the body.

There are many variables which play a part in determining the cooling efficiency of sweat evaporation and the findings of different investigators are not in agreement. Burton⁽⁴⁾ states that cooling efficiency for completely wet clothing is equal to

$$\frac{I_a}{I_{cw} + I_a}$$

If the previously used value, $I_{cw} = 0.4$, is substituted in this equation, the cooling efficiencies at 30 and 100 feet per minute air velocities would be 68 and 57.5 percent, respectively. If this value of 57.5 percent is applied to the above calculated evaporative cooling rate of 975 Btu/hr, the total latent heat addition to a space at 120 F and 100 feet per minute velocity would be

$$\frac{975}{.575} = 1700 \text{ Btu/hr per occupant.}$$

The latent loss from a nude subject at the same environmental conditions, as shown in Figure 7, is 1450 Btu/hr.

It will be noted that Burton's equation for cooling efficiency would indicate 100 percent efficiency for a nude subject. Givoni's⁽¹²⁾ work indicates an average efficiency of 95 percent for the nude body; most of

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the loss in efficiency is apparently due to drippage of sweat. It is therefore believed that the heat transfer data shown in Figures 6, 7 and 8 for nude subjects may be used without correction.

The above discussion would seem to suggest that as conditions in a shelter become warmer, occupants should be encouraged to remove clothing down to the minimal level. It is agreed by all investigators that in the warm humid environments likely to occur in survival shelters, occupants will be more comfortable with a minimum of clothing. And as suggested by the above example, under some conditions the total moisture addition to the space may be less from nude than from clothed subjects.

MAXIMUM LATENT HEAT LOSS RATES

All of the above discussion has been concerned with the heat losses required at various conditions to maintain the body in a state of thermal equilibrium. It has been pointed out that at elevated ambient temperatures all of the heat loss must take place by evaporation. The required extent of this evaporative loss is shown by the latent heat curves in Figures 3 through 8.

The maximum latent heat loss, E_{\max} , which the body can lose to the ambient air is a function of the air velocity, and the difference between the vapor pressure of the sweat on the skin, and the partial pressure of the water vapor in the air. This loss may be calculated from the denominator of the equation given on page 15 of reference 3, which is based on Burton's work.⁽⁴⁾ For the average nude man this equation, converted to the system of units used in this paper, may be written

$$E_{\max} = \frac{55.4 (42 - P_w)}{I_a} \quad (6)$$

Where:

P_w = partial pressure of the water vapor in air - mm Hg.

42 = vapor pressure of the sweat for a skin temperature of approximately 95 F - mm Hg.

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Values of E_{\max} calculated by this equation are shown by horizontal lines in Figures 11, 12 and 13, for air velocities of 30, 100 and 150 feet per minute, respectively. The lines are shown only to the right of the 95 F dry bulb line, since it is only in this region that the skin temperature remains relatively constant. (See Figure 1.) It is also only in the higher temperature region that one is likely to be interested in E_{\max} values. To the left of the 95 F line, the E_{\max} lines would turn downward because of the decreasing skin temperature.

The value of E_{\max} may also be limited by the ability of the body to produce sweat. This limitation is encountered most frequently under hot, dry conditions. Belding and Hatch⁽¹³⁾ state that the maximum rate of sweating which can be maintained by the average acclimatized man over an eight-hour period is 1 liter per hour. The evaporation of this quantity of sweat will produce a cooling effect of approximately 2400 Btu/hr. The 2400 E_{\max} line is shown dotted on Figures 11, 12 and 13. For the attainment of high sweat rates it is essential that the individual be supplied with sufficient drinking water to maintain normal body hydration.

To give meaning to the E_{\max} lines, three relative strain lines have also been drawn on Figures 11, 12 and 13. Lee and Henschel⁽³⁾ have defined relative strain as the ratio of the evaporative cooling required to maintain thermal equilibrium to the maximum rate of evaporative cooling which can be maintained in a given environment. For the average nude man the equation for this relationship may be written

$$\text{Relative strain} = \frac{M + \frac{22.8 (t_a - 95)}{I_a}}{\frac{55.4 (42 - P_w)}{I_a}} \quad (7)$$

At any point on the relative strain = 1.0 line, the evaporative cooling required to prevent body heat storage is equal to the maximum latent heat acceptance of the environment. This line thus defines the most severe conditions under which thermal equilibrium can be maintained. Similarly, the 0.50 relative strain line shows the conditions at which the required evaporative cooling is 50 percent of the maximum possible.

It should be noted that if, for example, 2400 Btu per hour is taken as the maximum possible cooling rate, then the relative strain lines would drop vertically downward from their intersection with the 2400 E_{\max} line.

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EFFECT OF PHYSICAL WORK ON BODY HEAT LOSS

It is assumed that the average person in a survival shelter will be essentially at rest, and the heat balance Equation (1) presented earlier in this report is for that condition. For a person performing useful work on an external system, the heat equivalent of that work would appear as an additional term on the right-hand side of the equation, and the heat loss by other methods required to maintain equilibrium would be reduced by that amount. The heat exchanges for persons at elevated metabolic rates may be calculated from the equations included in this report.

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TABLE I. AVERAGE HEIGHT AND WEIGHT OF MALES AND FEMALES
OF VARIOUS AGES IN THE U. S. A.

Age Years	Male		Female	
	Height inches	Weight pounds	Height inches	Weight pounds
4	40.9	30.2	40.9	37.3
5	43.9	43.2	43.6	42.0
6	46.1	47.6	45.8	46.4
7	48.2	52.5	47.9	51.2
8	50.4	58.2	50.0	56.9
9	52.4	64.4	52.0	63.0
10	54.3	70.7	54.2	70.3
11	56.2	77.6	56.5	79.0
12	58.2	85.6	59.0	89.7
13	60.5	95.6	60.6	100.3
14	63.0	107.9	62.3	108.5
15	65.5	121.7	63.2	115.0
16	67.3	131.9	63.5	117.6
17	67.6	140.4	63.6	119.0
18	68.2	147.8	64.3	125.6
19	68.3	151.2	64.7	128.6
20-24	68.4	154.7	63.6	123.0
25-29	68.3	157.8	63.4	124.7
30-34	68.1	158.1	63.4	129.5
35-44	--	--	63.1	138.0
45-54	--	--	62.8	147.8
55-64	--	--	62.2	144.5
>64	--	--	61.7	138.5

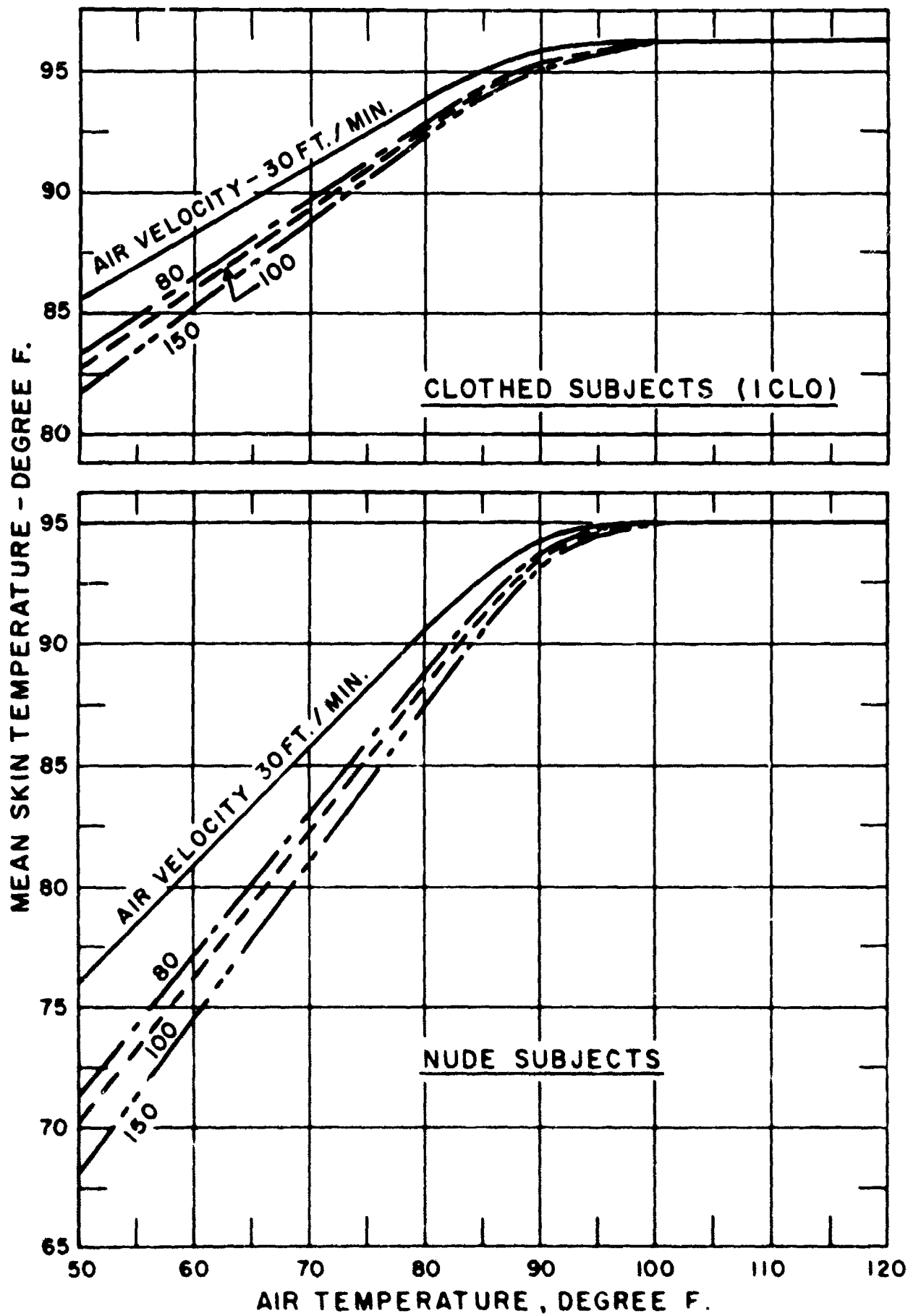


Figure 1 - Skin Temperatures of Clothed and Nude Subjects

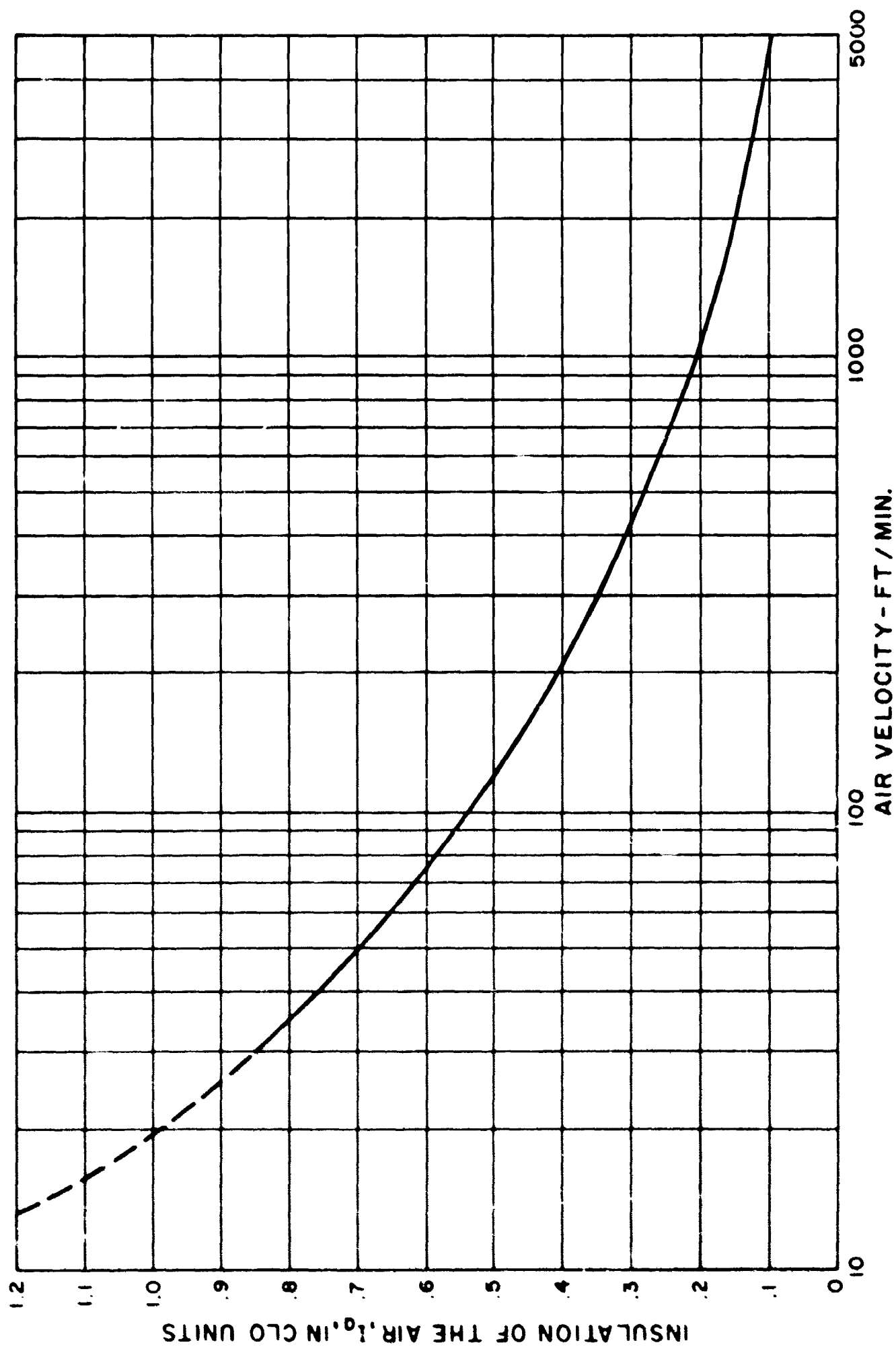


Figure 2 - Insulation of Air, I_a vs. Air Velocity

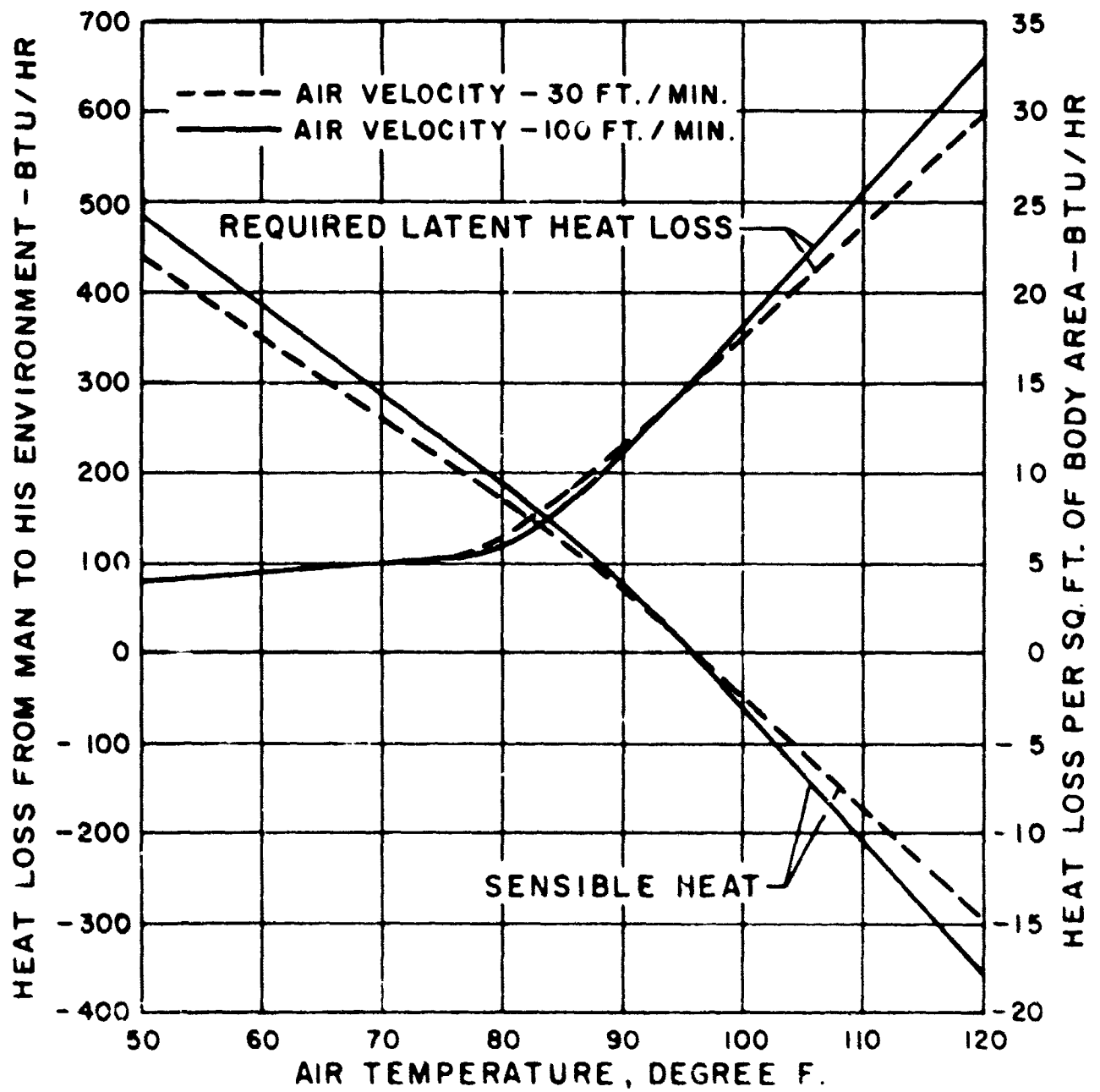


Figure 3 - Heat Loss from Clothed Supine Resting Subjects. Metabolic Rate = 300 Btu/hr., (15 Btu/(hr)(sq. ft.)), $S = 0$

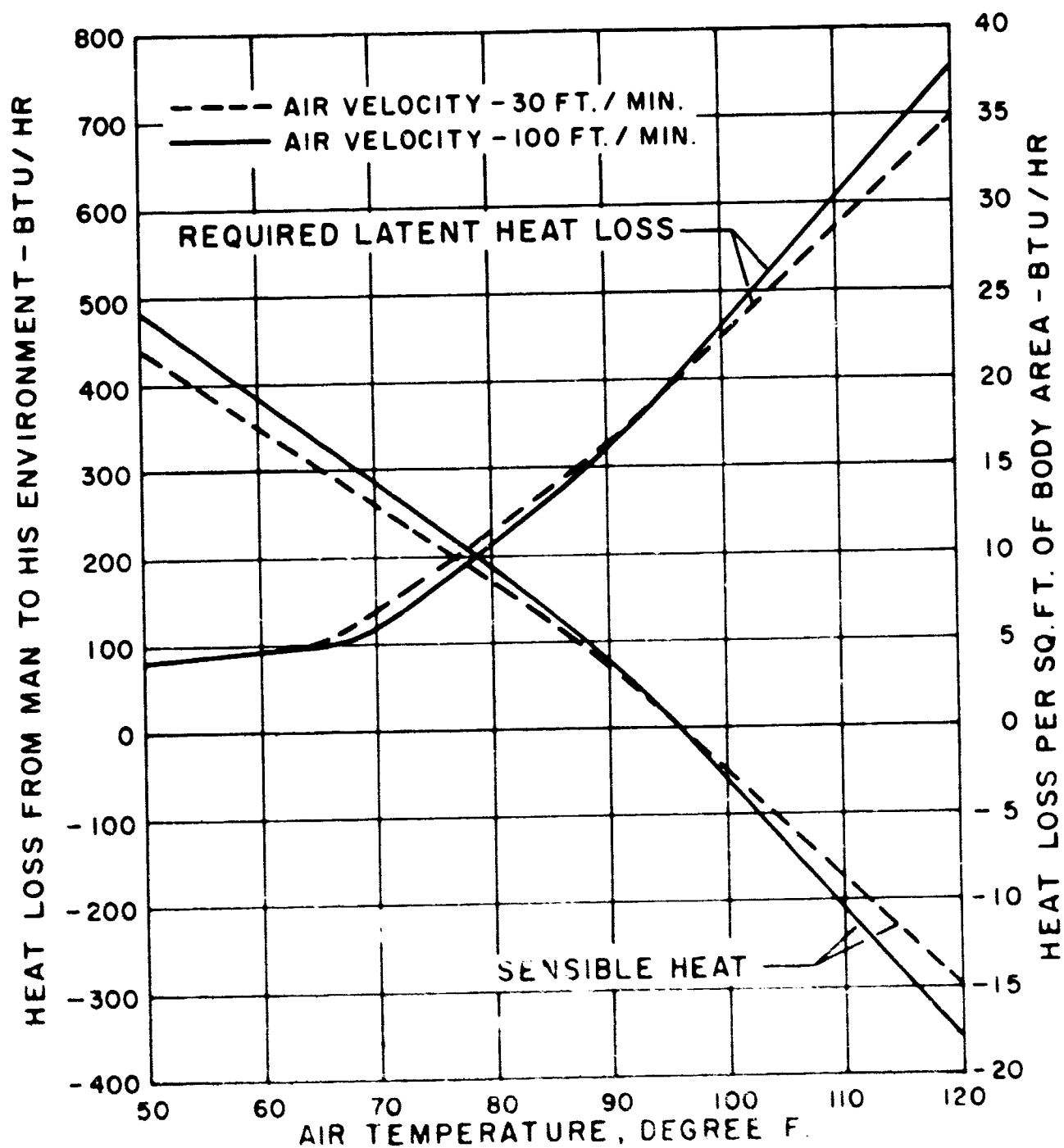


Figure 4 - Heat Loss from Clothed Subjects, Seated, at Rest.
 Metabolic Rate = 400 Btu/hr., (20 Btu/hr. per sq. ft. of body area).
 $S = 0$

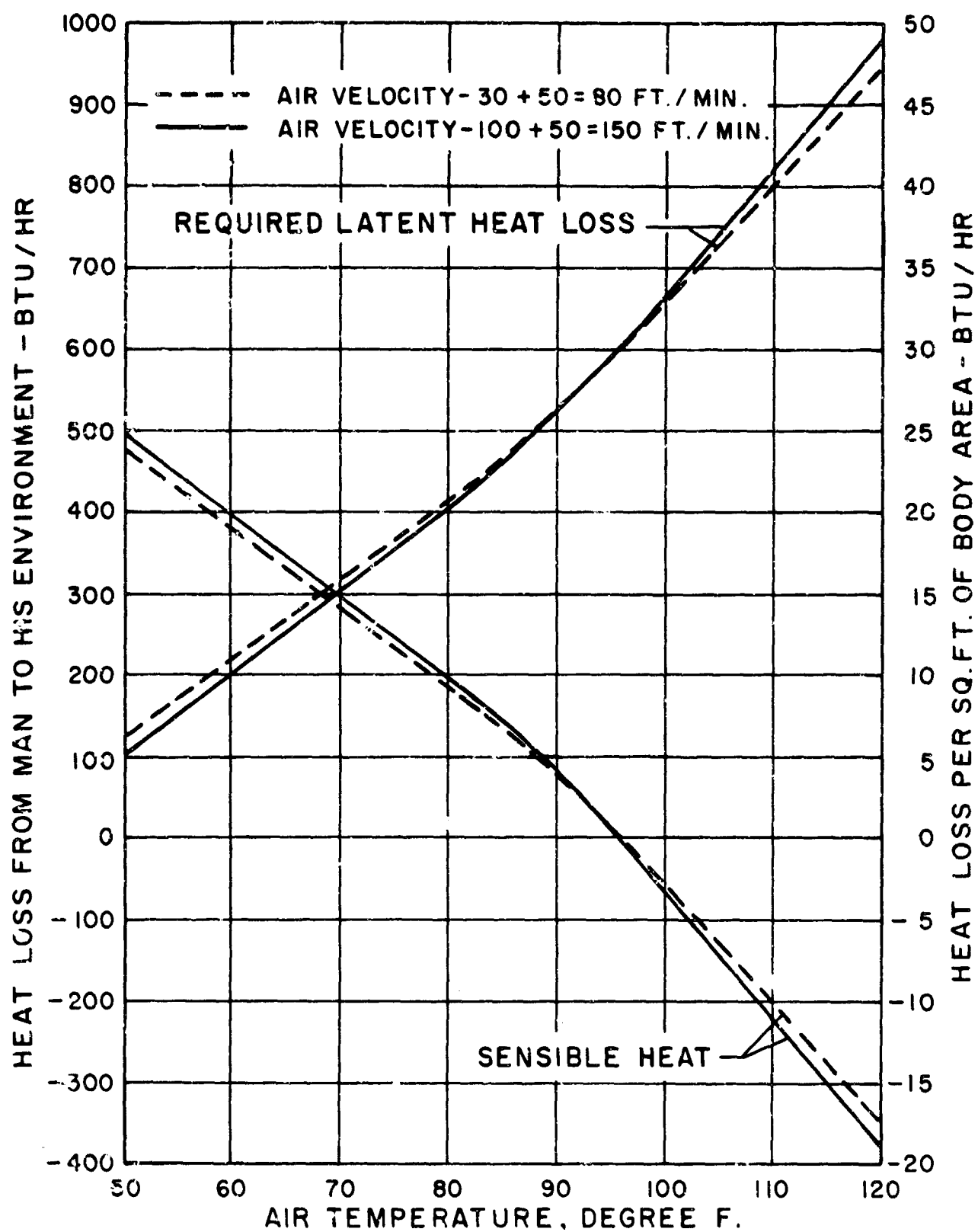


Figure 5 - Heat Loss from Clothed Subjects Doing Light Work.
 Metabolic Rate = 600 Btu/hr., (30 Btu/(hr.)(sq.ft.)),
 $S = 0$

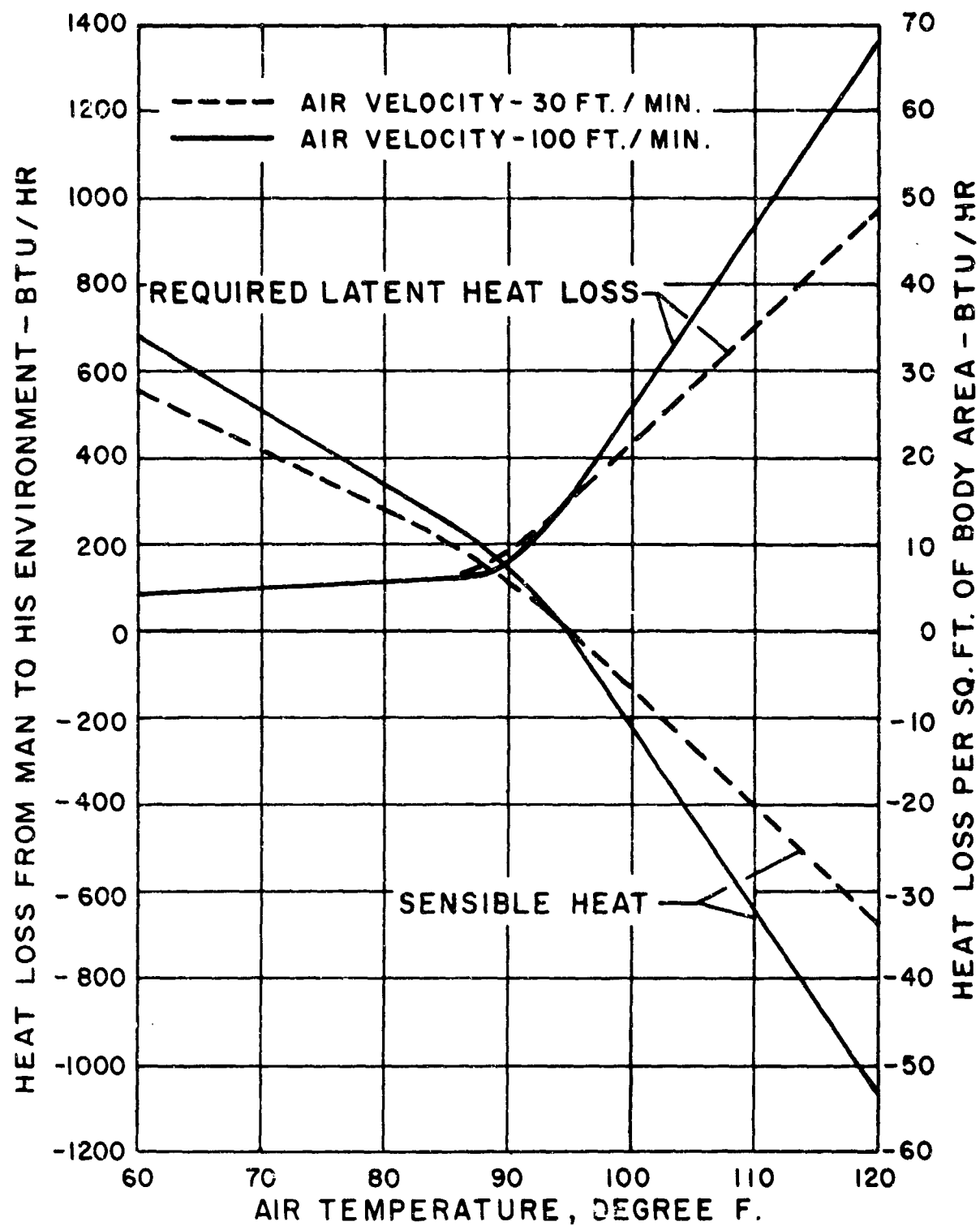


Figure 6 - Heat Loss from Nude Supine Resting Subjects. Metabolic Rate = 300 Btu/hr., (15 Btu/(hr.)(sq.ft.)), $S = 0$

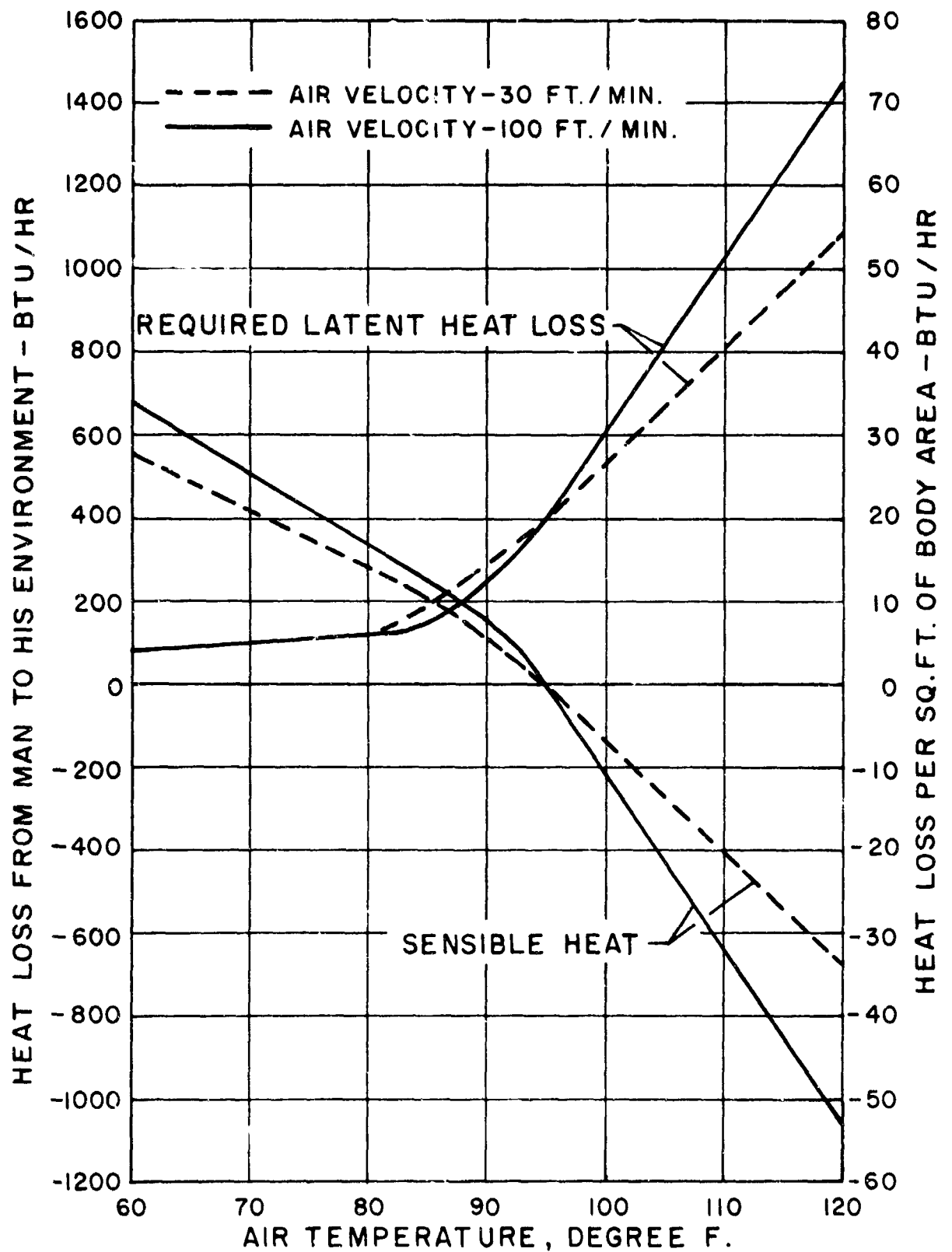


Figure 7 - Heat Loss from Nude Subjects, Seated, at Rest.
 Metabolic Rate = 400 Btu/hr., (20 Btu/(hr.)(sq.ft.)),
 $S = 0$

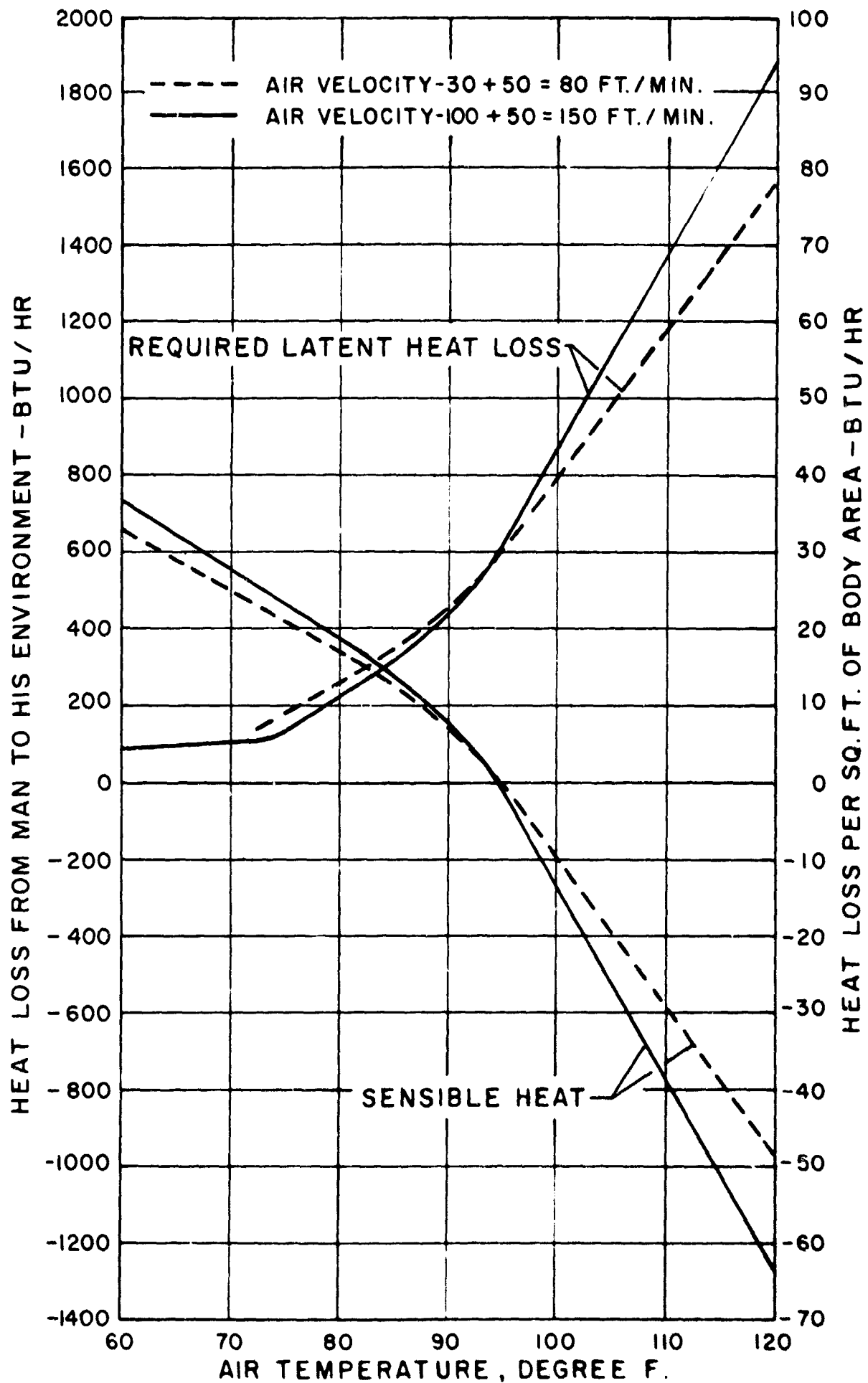
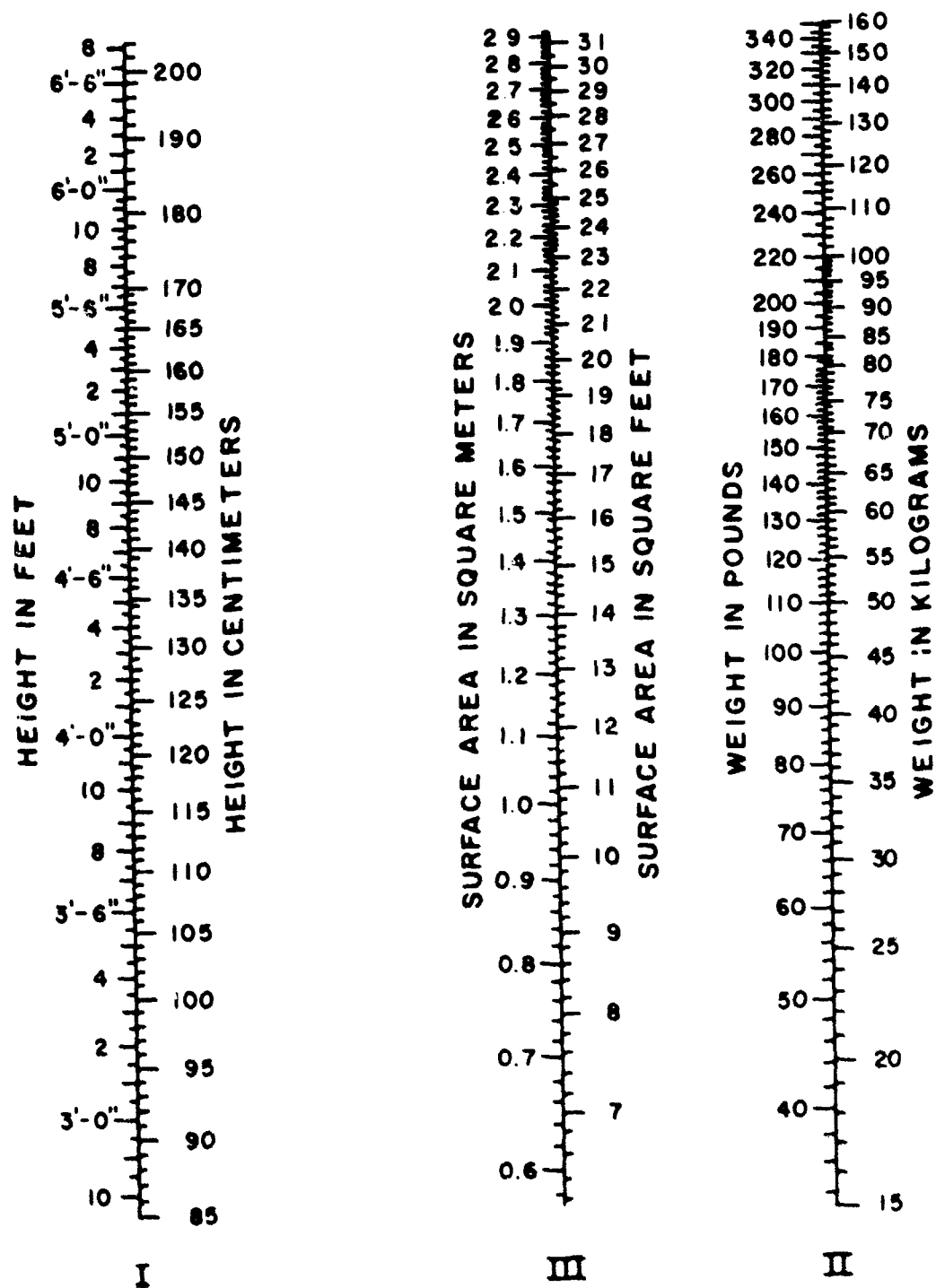


Figure 8 - Heat Loss from Nude Subjects Doing Light Work.
 Metabolic Rate = 600 Btu/hr., (30 Btu/(hr.)(sq.ft.)),
 $S = 0$



DIRECTIONS

To find the body surface area of a subject draw a line from his height (Scale I) to his weight (Scale II) and read area on Scale III .

Figure 9 - Du Bois Body Surface Chart

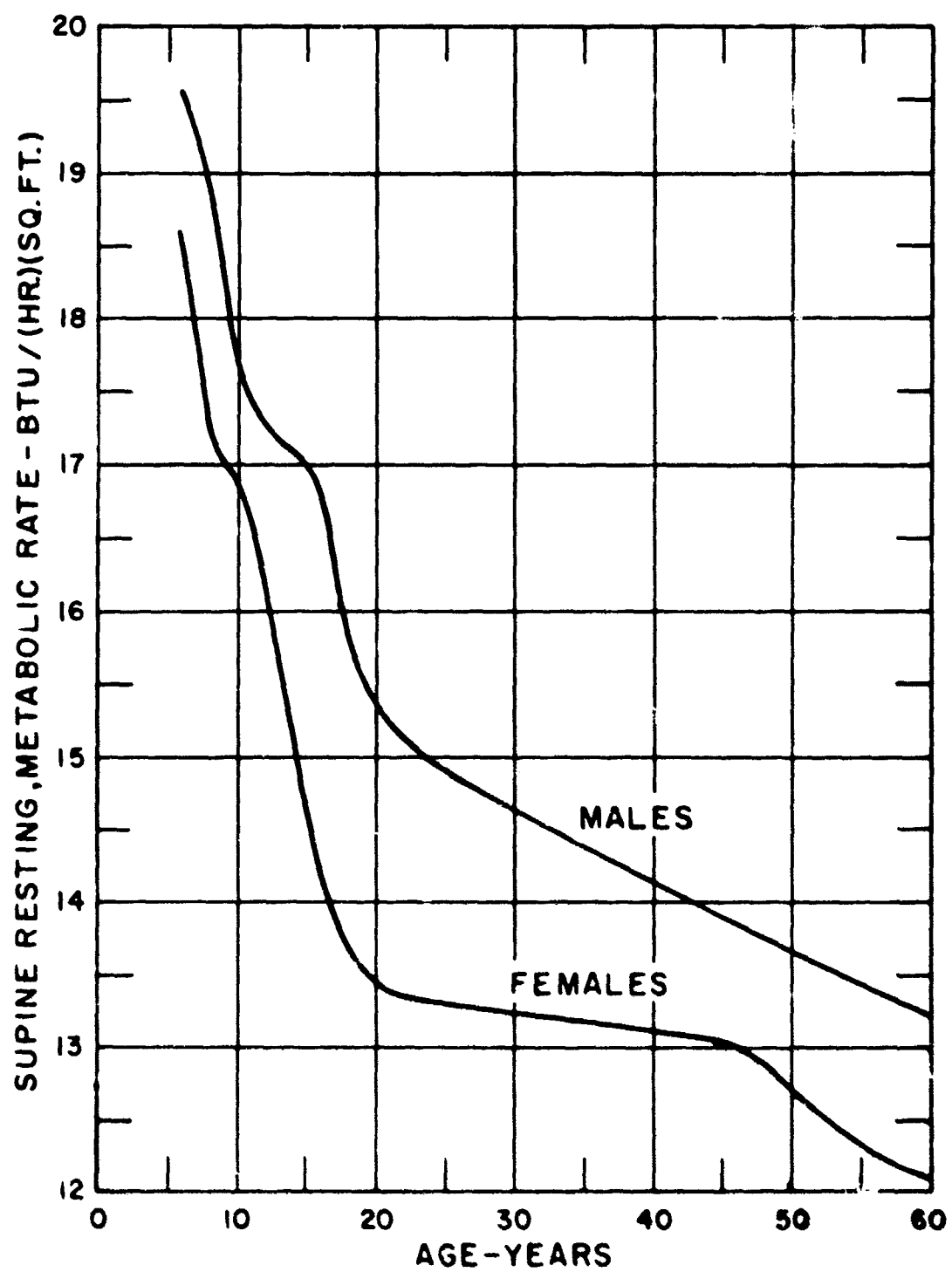


Figure 10 - Supine Resting Metabolic Rate vs. Age

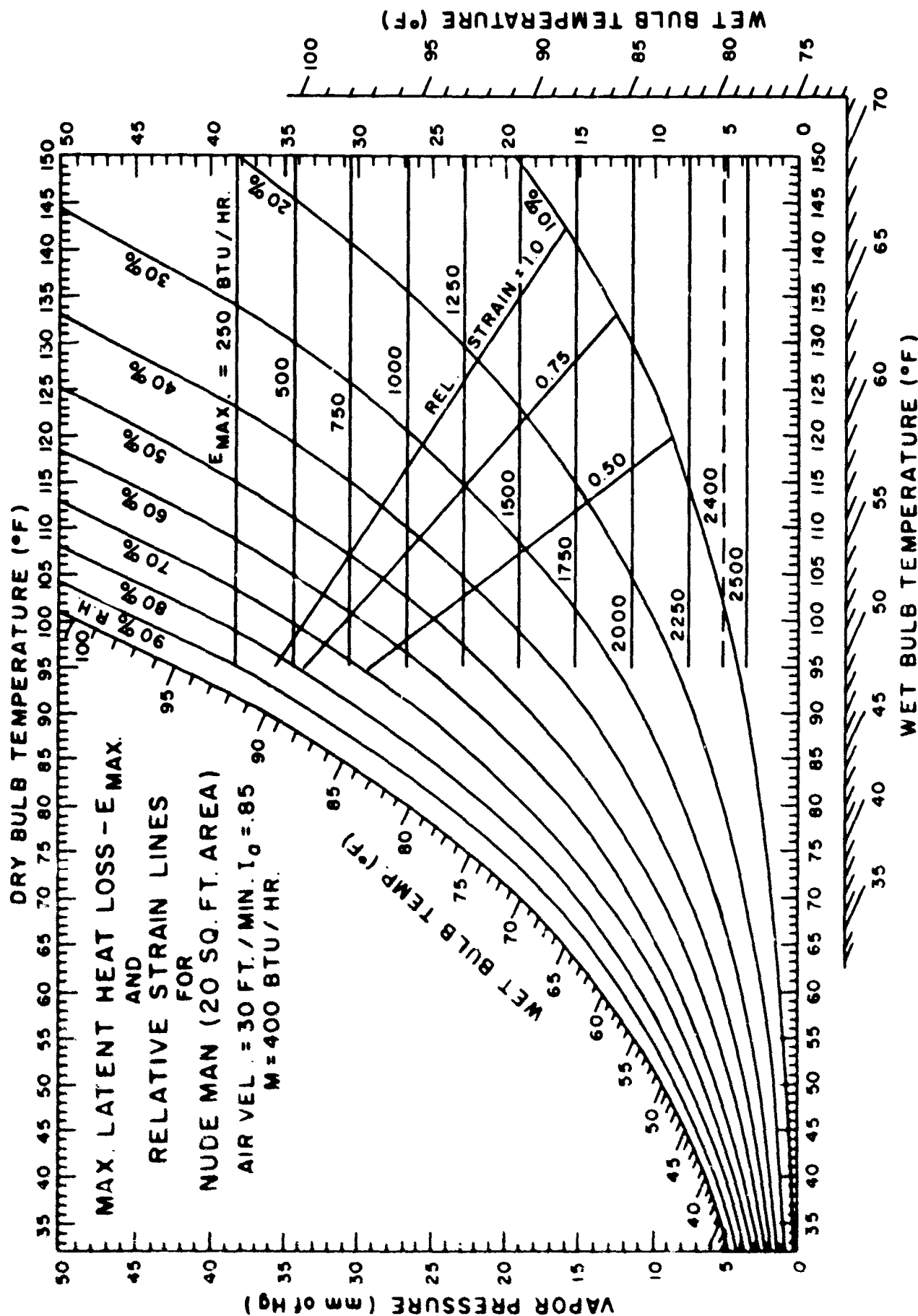


Figure 11 - Maximum Latent Heat Losses and Relative Strain for Nude Subjects
 $M = 400$ Btu/hr., Air Velocity = 30 ft./min.

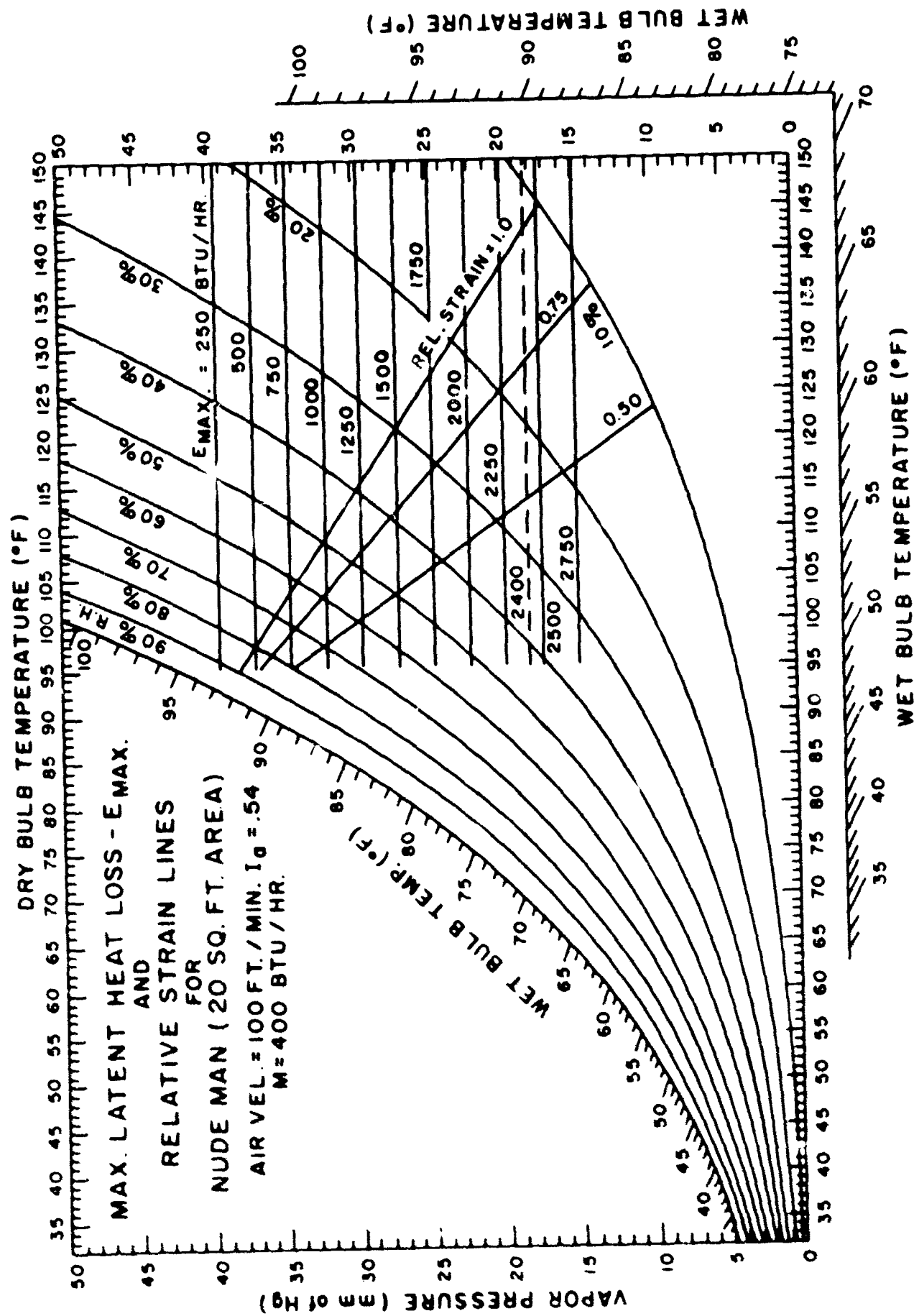


Figure 12 - Maximum Latent Heat Losses and Relative Strain for Nude Subjects
 $M = 400$ Btu/hr., Air Velocity = 100 ft./min.

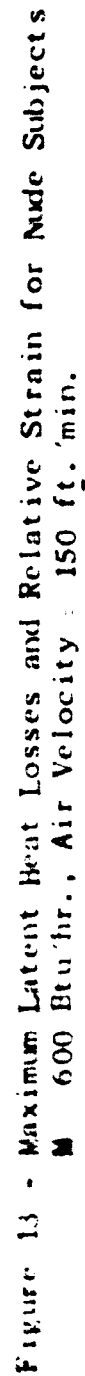


Figure 13 - Maximum Latent Heat Losses and Relative Strain for Nude Subjects
M 600 Btu/hr., Air Velocity = 150 ft./min.

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13 ABSTRACT Six figures have been prepared showing the sensible and latent heat exchange rates from clothed and nude individuals at various environmental conditions and at three metabolic rates. Data are also included by which the heat exchange rates for the "standard individual" may be corrected for "non-standard" groups.			

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